

# Search for $Z_{s1}^+$ and $Z_{s2}^+$ strangeonium-like structures

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(Dated: May 28, 2012)

Theoretically, it has been presumed from an effective Lagrangian calculation that there could exist two charged strangeonium-like molecular states  $Z_{s1}^+$  and  $Z_{s2}^+$ , with  $K\bar{K}^*$  and  $K^*\bar{K}^*$  configurations respectively. In the framework of QCD sum rules, we predict that masses of  $Z_{s1}^+$  ( $K\bar{K}^*$ ) and  $Z_{s2}^+$  ( $K^*\bar{K}^*$ ) are  $1.85 \pm 0.14$  GeV and  $2.02 \pm 0.15$  GeV respectively, which are both above their respective two meson thresholds. We suggest to put in practice the search for these two charged strangeonium-like structures in future experiments.

PACS numbers: 11.55.Hx, 12.38.Lg, 12.39.Mk

## I. INTRODUCTION

Recently, Liu *et al.* study the  $\phi(1020)\pi^+$  invariant mass spectrum distribution of  $Y(2175) \rightarrow \phi(1020)\pi^+\pi^-$  and indicate that there could exist two charged molecular states  $Z_{s1}^+$  and  $Z_{s2}^+$ , whose configurations are  $K\bar{K}^*$  and  $K^*\bar{K}^*$  respectively [1]. The molecular state is well and truly not a new concept but with a history, which was put forward long ago in Ref. [2] and has also been predicted that molecular states have a rich spectroscopy in Ref. [3]. Since there is not any restriction for the number of quarks inside a hadron, QCD does not exclude the existence of multi-quark states such as molecular states. In fact, some of the so-called X, Y, and Z resonances have already been ranked as possible charmonium-like molecular candidates. For example,  $X(4350)$  is interpreted as a  $D_s^*D_s^{0*}$  state [4, 5];  $Y(3930)$  is proposed to be a  $D^*\bar{D}^*$  state [6–8];  $Y(4140)$  is deciphered as a  $D_s^*\bar{D}_s^*$  state [7, 9];  $Y(4260)$  could be a  $\chi_{c1}\rho^0$  [10] or an  $\omega\chi_{c1}$  state [11];  $Y(4274)$  is investigated as a  $D_sD_{s0}(2317)$  state [12];  $Z^+(4430)$  is suggested to be a  $D^*\bar{D}_1$  molecular state [13]. For more molecular candidates, one can also see some other reviews, e.g. Ref. [14].

The two  $Z_{s1}^+$  and  $Z_{s2}^+$  resonances may shed light on studying strangeonium-like molecular states. Their properties like masses are important and helpful for searching them in future experiments. Unfortunately, quarks are confined inside hadrons in the real world, and the strong interaction dynamics of  $K\bar{K}^*$  and  $K^*\bar{K}^*$  systems are governed by nonperturbative QCD effect completely. The quantitative calculations of hadronic properties run into arduous difficulties. However, one can apply the QCD sum rule method [15] (for reviews see [16–19] and references therein), which is a nonperturbative formulation firmly based on QCD basic theory and has been successfully employed to research some light four-quark states [20–25]. In this work, we are devoted to predicting masses of  $Z_{s1}^+$  and  $Z_{s2}^+$  from QCD sum rules.

The rest of the paper is organized as three parts. We discuss QCD sum rules for molecular states in Sec. II with the similar procedure as our previous works [26, 27], where the phenomenological representation and the operator product expansion (OPE) contribution up to dimension ten operators for the two-point correlator are derived. The numerical analysis is made in Sec. III, and masses of  $Z_{s1}^+$  ( $K\bar{K}^*$ ) and  $Z_{s2}^+$  ( $K^*\bar{K}^*$ ) are extracted out. The Sec. IV includes a brief summary and outlook.

## II. QCD SUM RULES FOR $Z_{s1}^+$ AND $Z_{s2}^+$ MOLECULAR STATES

An elementary step of the QCD sum rule method is the choice of interpolating current. Following the standard scheme [28], strange mesons with  $J^P = 0^-$  and  $1^-$  are named as  $K$  and  $K^*$ . In full QCD, interpolating currents for these mesons can be found in Ref. [29]. One could construct the molecular state current from meson-meson type of fields. Thus, the following form of current could be constructed for

$K\bar{K}^*$ ,

$$j_{K\bar{K}^*}^\mu = (\bar{s}_c i \gamma_5 q_c)(\bar{q}'_{c'} \gamma^\mu s_{c'}), \quad (1)$$

where  $q$  and  $q'$  denote light quarks  $u$  and  $d$ ,  $c$  and  $c'$  are color indices, and the quantum number for the current is  $1^+$ . Lorentz covariance implies that the two-point correlator  $\Pi^{\mu\nu}(q^2) = i \int d^4x e^{iq \cdot x} \langle 0 | T[j^\mu(x) j^{\nu+}(0)] | 0 \rangle$  can be generally parameterized as

$$\Pi^{\mu\nu}(q^2) = \left( \frac{q^\mu q^\nu}{q^2} - g^{\mu\nu} \right) \Pi^{(1)}(q^2) + \frac{q^\mu q^\nu}{q^2} \Pi^{(0)}(q^2), \quad (2)$$

where  $\Pi^{(1)}(q^2)$  is pure vector and  $\Pi^{(0)}(q^2)$  is related to the scalar current correlation function. In phenomenology, the calculation proceeds by inserting intermediate states for  $K\bar{K}^*$ . Parameterizing the coupling of the state  $K\bar{K}^*$  to the current  $j_{K\bar{K}^*}^\mu$  in terms of the coupling constant  $\lambda^{(1)}$  as  $\langle 0 | j_{K\bar{K}^*}^\mu | K\bar{K}^* \rangle = \lambda^{(1)} \epsilon^\mu$ , the phenomenological side of  $\Pi^{\mu\nu}(q^2)$  can be expressed as

$$\Pi^{\mu\nu}(q^2) = \left( \frac{q^\mu q^\nu}{M_{K\bar{K}^*}^2} - g^{\mu\nu} \right) \left\{ \frac{[\lambda^{(1)}]^2}{M_{K\bar{K}^*}^2 - q^2} + \frac{1}{\pi} \int_{s_0}^{\infty} ds \frac{\text{Im} \Pi^{(1)\text{phen}}(s)}{s - q^2} + \text{subtractions} \right\}, \quad (3)$$

where  $M_{K\bar{K}^*}$  denotes the mass of the  $K\bar{K}^*$  resonance, and  $s_0$  is the threshold parameter. The Lorentz structure  $g^{\mu\nu}$  gets contributions only from the spin 1 state, which is chosen to extract the mass sum rule. In the OPE side,  $\Pi^{(1)}(q^2)$  can be written as

$$\Pi^{(1)}(q^2) = \int_{4m_s^2}^{\infty} ds \frac{\rho^{\text{OPE}}(s)}{s - q^2} + \Pi^{(1)\text{cond}}(q^2), \quad (4)$$

where the spectral density is  $\rho^{\text{OPE}}(s) = \frac{1}{\pi} \text{Im} \Pi^{(1)}(s)$ . After equating the two sides, assuming quark-hadron duality, and making a Borel transform, the sum rule can be written as

$$[\lambda^{(1)}]^2 e^{-M_{K\bar{K}^*}^2/M^2} = \int_{4m_s^2}^{s_0} ds \rho^{\text{OPE}} e^{-s/M^2} + \hat{B} \Pi^{(1)\text{cond}}. \quad (5)$$

where  $M^2$  indicates Borel parameter. To eliminate the hadronic coupling constant  $\lambda^{(1)}$ , one reckons the ratio of derivative of the sum rule to itself, and then yields

$$M_{K\bar{K}^*}^2 = \left\{ \int_{4m_s^2}^{s_0} ds \rho^{\text{OPE}} e^{-\frac{s}{M^2}} + \frac{d(\hat{B} \Pi^{(1)\text{cond}})}{d(-\frac{1}{M^2})} \right\} / \left\{ \int_{4m_s^2}^{s_0} ds \rho^{\text{OPE}} e^{-\frac{s}{M^2}} + \hat{B} \Pi^{(1)\text{cond}} \right\}. \quad (6)$$

The current for  $K^* \bar{K}^*$  could be constructed as

$$j_{K^* \bar{K}^*} = (\bar{s}_c \gamma^\mu q_c)(\bar{q}'_c \gamma_\mu s_{c'}), \quad (7)$$

with the quantum number  $0^+$ . Phenomenologically, the correlator  $\Pi(q^2) = i \int d^4x e^{iq \cdot x} \langle 0 | T[j(x) j^+(0)] | 0 \rangle$  can be expressed as

$$\Pi(q^2) = \frac{\lambda_{K^* \bar{K}^*}^2}{M_{K^* \bar{K}^*}^2 - q^2} + \frac{1}{\pi} \int_{s_0}^{\infty} ds \frac{\text{Im} \Pi^{\text{phen}}(s)}{s - q^2} + \text{subtractions}, \quad (8)$$

where  $M_{K^* \bar{K}^*}$  denotes the mass of the  $K^* \bar{K}^*$  resonance, and  $\lambda_{K^* \bar{K}^*}$  gives the coupling of the current to the hadron  $\langle 0 | j | K^* \bar{K}^* \rangle = \lambda_{K^* \bar{K}^*}$ . In the OPE side, the correlator can be written as

$$\Pi(q^2) = \int_{4m_s^2}^{\infty} ds \frac{\rho^{\text{OPE}}(s)}{s - q^2} + \Pi^{\text{cond}}(q^2), \quad (9)$$

where the spectral density is  $\rho^{\text{OPE}}(s) = \frac{1}{\pi} \text{Im} \Pi^{\text{OPE}}(s)$ . Then, the sum rule can be written as

$$\lambda_{K^* \bar{K}^*}^2 e^{-M_{K^* \bar{K}^*}^2/M^2} = \int_{4m_s^2}^{s_0} ds \rho^{\text{OPE}} e^{-s/M^2} + \hat{B} \Pi^{\text{cond}}. \quad (10)$$

Eliminating the hadronic coupling constant  $\lambda_{K^* \bar{K}^*}$ , one yields

$$M_{K^* \bar{K}^*}^2 = \left\{ \int_{4m_s^2}^{s_0} ds \rho^{\text{OPE}} e^{-\frac{s}{M^2}} + \frac{d(\hat{B} \Pi^{\text{cond}})}{d(-\frac{1}{M^2})} \right\} / \left\{ \int_{4m_s^2}^{s_0} ds \rho^{\text{OPE}} e^{-\frac{s}{M^2}} + \hat{B} \Pi^{\text{cond}} \right\}. \quad (11)$$

For the OPE calculations, we work at the leading order in  $\alpha_s$  and consider condensates up to dimension ten, utilizing the light-quark propagator in the coordinate-space

$$\begin{aligned} S_{ab}(x) = & \frac{i\delta_{ab}}{2\pi^2 x^4} \not{x} - \frac{m_q \delta_{ab}}{4\pi^2 x^2} - \frac{i}{32\pi^2 x^2} t_{ab}^A g G_{\mu\nu}^A (\not{x} \sigma^{\mu\nu} + \sigma^{\mu\nu} \not{x}) - \frac{\delta_{ab}}{12} \langle \bar{q}q \rangle + \frac{i\delta_{ab}}{48} m_q \langle \bar{q}q \rangle \not{x} \\ & - \frac{x^2 \delta_{ab}}{3 \cdot 2^6} \langle g \bar{q} \sigma \cdot G q \rangle + \frac{i x^2 \delta_{ab}}{2^7 \cdot 3^2} m_q \langle g \bar{q} \sigma \cdot G q \rangle \not{x} - \frac{x^4 \delta_{ab}}{2^{10} \cdot 3^3} \langle \bar{q}q \rangle \langle g^2 G^2 \rangle. \end{aligned}$$

The  $s$  quark is dealt as a light one and the diagrams are considered up to the order  $m_s$ . The spectral density can be written as  $\rho^{\text{OPE}}(s) = \rho^{\text{pert}}(s) + \rho^{\langle \bar{q}q \rangle}(s) + \rho^{\langle \bar{s}s \rangle}(s) + \rho^{\langle \bar{q}q \rangle \langle \bar{s}s \rangle}(s) + \rho^{\langle g \bar{q} \sigma \cdot G q \rangle}(s) + \rho^{\langle g \bar{s} \sigma \cdot G s \rangle}(s) + \rho^{\langle g^2 G^2 \rangle}(s) + \rho^{\langle \bar{q}q \rangle \langle g^2 G^2 \rangle}(s) + \rho^{\langle \bar{q}q \rangle \langle g \bar{s} \sigma \cdot G s \rangle}(s) + \rho^{\langle \bar{s}s \rangle \langle g \bar{q} \sigma \cdot G q \rangle}(s)$ , where  $\rho^{\text{pert}}$ ,  $\rho^{\langle \bar{q}q \rangle}$ ,  $\rho^{\langle \bar{q}q \rangle \langle \bar{s}s \rangle}$ ,  $\rho^{\langle g \bar{q} \sigma \cdot G q \rangle}$ , and  $\rho^{\langle g^2 G^2 \rangle}$  are the perturbative, quark condensate, four-quark condensate, mixed condensate, and two-gluon condensate spectral densities, respectively. They are

$$\rho^{\text{pert}}(s) = \frac{1}{3 \cdot 2^{15} \pi^6} s^4, \quad \rho^{\langle \bar{q}q \rangle}(s) = -\frac{7 \langle \bar{q}q \rangle}{2^{10} \pi^4} m_s s^2, \quad \rho^{\langle \bar{s}s \rangle}(s) = \frac{3 \langle \bar{s}s \rangle}{2^{10} \pi^4} m_s s^2, \quad \rho^{\langle \bar{q}q \rangle \langle \bar{s}s \rangle}(s) = \frac{5 \langle \bar{q}q \rangle \langle \bar{s}s \rangle}{3 \cdot 2^5 \pi^2} s,$$

$$\rho^{\langle g \bar{q} \sigma \cdot G q \rangle}(s) = \frac{5 \langle g \bar{q} \sigma \cdot G q \rangle}{2^9 \pi^4} m_s s, \quad \rho^{\langle g \bar{s} \sigma \cdot G s \rangle}(s) = -\frac{\langle g \bar{s} \sigma \cdot G s \rangle}{3 \cdot 2^7 \pi^4} m_s s, \quad \rho^{\langle g^2 G^2 \rangle}(s) = \frac{\langle g^2 G^2 \rangle}{3 \cdot 2^{13} \pi^6} s^2,$$

$$\rho^{\langle \bar{q}q \rangle \langle g^2 G^2 \rangle}(s) = -\frac{\langle \bar{q}q \rangle \langle g^2 G^2 \rangle}{2^{11} \pi^4} m_s, \quad \rho^{\langle \bar{q}q \rangle \langle g \bar{s} \sigma \cdot G s \rangle}(s) = -\frac{3 \langle \bar{q}q \rangle \langle g \bar{s} \sigma \cdot G s \rangle}{2^7 \pi^2}, \quad \rho^{\langle \bar{s}s \rangle \langle g \bar{q} \sigma \cdot G q \rangle}(s) = -\frac{3 \langle \bar{s}s \rangle \langle g \bar{q} \sigma \cdot G q \rangle}{2^7 \pi^2},$$

$$\hat{B} \Pi^{(1) \text{cond}} = \frac{m_s \langle \bar{s}s \rangle^2 \langle \bar{q}q \rangle}{3 \cdot 2^3} - \frac{m_s \langle \bar{q}q \rangle^2 \langle \bar{s}s \rangle}{3 \cdot 2} + \frac{\langle g \bar{q} \sigma \cdot G q \rangle \langle g \bar{s} \sigma \cdot G s \rangle}{2^8 \pi^2} + \frac{\langle \bar{q}q \rangle \langle \bar{s}s \rangle \langle g^2 G^2 \rangle}{3^2 \cdot 2^7 \pi^2},$$

for  $K \bar{K}^*$ , and

$$\rho^{\text{pert}}(s) = \frac{1}{5 \cdot 2^{12} \pi^6} s^4, \quad \rho^{\langle \bar{q}q \rangle}(s) = -\frac{\langle \bar{q}q \rangle}{2^6 \pi^4} m_s s^2, \quad \rho^{\langle \bar{s}s \rangle}(s) = \frac{\langle \bar{s}s \rangle}{2^6 \pi^4} m_s s^2, \quad \rho^{\langle \bar{q}q \rangle \langle \bar{s}s \rangle}(s) = \frac{\langle \bar{q}q \rangle \langle \bar{s}s \rangle}{2^3 \pi^2} s,$$

$$\rho^{\langle g \bar{q} \sigma \cdot G q \rangle}(s) = \frac{3 \langle g \bar{q} \sigma \cdot G q \rangle}{2^7 \pi^4} m_s s, \quad \rho^{\langle g \bar{s} \sigma \cdot G s \rangle}(s) = -\frac{\langle g \bar{s} \sigma \cdot G s \rangle}{2^6 \pi^4} m_s s, \quad \rho^{\langle \bar{q}q \rangle \langle g^2 G^2 \rangle}(s) = -\frac{\langle \bar{q}q \rangle \langle g^2 G^2 \rangle}{3 \cdot 2^8 \pi^4} m_s,$$

$$\rho^{\langle \bar{q}q \rangle \langle g \bar{s} \sigma \cdot G s \rangle}(s) = -\frac{\langle \bar{q}q \rangle \langle g \bar{s} \sigma \cdot G s \rangle}{2^4 \pi^2}, \quad \rho^{\langle \bar{s}s \rangle \langle g \bar{q} \sigma \cdot G q \rangle}(s) = -\frac{\langle \bar{s}s \rangle \langle g \bar{q} \sigma \cdot G q \rangle}{2^4 \pi^2},$$

$$\hat{B} \Pi^{\text{cond}} = \frac{m_s \langle \bar{s}s \rangle^2 \langle \bar{q}q \rangle}{3 \cdot 2} - \frac{2 m_s \langle \bar{q}q \rangle^2 \langle \bar{s}s \rangle}{3} + \frac{\langle g \bar{q} \sigma \cdot G q \rangle \langle g \bar{s} \sigma \cdot G s \rangle}{2^6 \pi^2} + \frac{\langle \bar{q}q \rangle \langle \bar{s}s \rangle \langle g^2 G^2 \rangle}{3^2 \cdot 2^5 \pi^2},$$

for  $K^* \bar{K}^*$ .

### III. NUMERICAL ANALYSIS AND DISCUSSIONS

Numerically, sum rules (6) and (11) are analyzed in this section. The input values are taken as  $m_s = 0.10^{+0.03}_{-0.02}$  GeV [28],  $\langle \bar{q}q \rangle = -(0.23 \pm 0.03)^3$  GeV<sup>3</sup>,  $\langle g\bar{q}\sigma \cdot Gq \rangle = m_0^2 \langle \bar{q}q \rangle$ ,  $\langle \bar{s}s \rangle = -(0.8 \pm 0.1) \times (0.23 \pm 0.03)^3$  GeV<sup>3</sup>,  $\langle g\bar{s}\sigma \cdot Gs \rangle = m_0^2 \langle \bar{s}s \rangle$ ,  $m_0^2 = 0.8 \pm 0.1$  GeV<sup>2</sup>, and  $\langle g^2 G^2 \rangle = 0.88$  GeV<sup>4</sup> [17]. Complying with the standard criterion of sum rule analysis, the threshold  $s_0$  and Borel parameter  $M^2$  are varied to find the optimal stability window. In the QCD sum rule approach, one can analyse the convergence in the OPE side and the pole contribution dominance in the phenomenological side to determine the allowed Borel window. Meanwhile, the threshold parameter  $\sqrt{s_0}$  is not completely arbitrary but characterizes the beginning of the continuum state, and the energy gap between the groundstate and the first excitation is around 0.5 GeV in many cases of light mesons and nucleons. In a word, it is expected that QCD sum rule's two sides have a good overlap in the work window and information on the resonance can be reliably obtained. For instance, the comparison between pole and continuum contributions from sum rule (10) for  $K^*\bar{K}^*$  for  $\sqrt{s_0} = 2.4$  GeV is shown in the left panel of FIG. 1, and its OPE convergence is shown in the right panel by comparing the perturbative, two-quark condensate, four-quark condensate, mixed condensate, two-quark multiply two-gluon condensate, two-quark multiply mixed condensate, six-quark condensate, mixed multiply mixed condensate, and four-quark multiply two-gluon condensate contributions. Note that the perturbative contribution is almost as large as the  $\langle qq \rangle \langle ss \rangle$  contribution at  $M^2 = 1.5$  GeV<sup>2</sup> (the ratio of  $\langle qq \rangle \langle ss \rangle$  to perturbative is approximate to 96%). Even if we choose some weak convergence criteria, e.g. the perturbative contribution should be 20% bigger than the second most important condensate, there is no standard OPE convergence at least up to  $M^2 \geq 1.8$  GeV<sup>2</sup> (the ratio of  $\langle qq \rangle \langle ss \rangle$  to perturbative is approximate to 79% at  $M^2 = 1.8$  GeV<sup>2</sup>). On the other hand, the relative pole contribution is approximate to 53% at  $M^2 = 1.3$  GeV<sup>2</sup> and descends along with the  $M^2$ . The consequence is that it is not possible to find a region where both the OPE normally converges and the pole dominates over the continuum. The problem with the sum rule is that the perturbative contribution is smaller than the four-quark condensate contribution while the pole contribution is bigger than the continuum contribution. Releasing the above standard convergence criteria of OPE, we consider the ratio of perturbative contribution to the “total OPE contribution” (the sum of perturbative and other condensate contributions calculated) but not the ratio of perturbative contribution to each condensate contribution. Not bad, there are enumerably important condensate contributions (four-quark condensate and two-quark multiply mixed condensate) and other condensate contributions are much smaller than the perturbative contribution. Two important condensate contributions could cancel with each other to some extent, which brings that the ratio of perturbative contribution to the “total OPE contribution” is 71% at  $M^2 = 0.7$  GeV<sup>2</sup> and increases with the  $M^2$ . In this sense, the OPE converges when  $M^2 \geq 0.7$  GeV<sup>2</sup> (note that the perturbative contribution of OPE series here is not always bigger than other terms in succession). Thus, the range of  $M^2$  for  $K^*\bar{K}^*$  is taken as  $M^2 = 0.7 \sim 1.3$  GeV<sup>2</sup> for  $\sqrt{s_0} = 2.4$  GeV. Similarly, the proper range of  $M^2$  is obtained as  $0.7 \sim 1.4$  GeV<sup>2</sup> for  $\sqrt{s_0} = 2.5$  GeV, and the range of  $M^2$  is  $0.7 \sim 1.5$  GeV<sup>2</sup> for  $\sqrt{s_0} = 2.6$  GeV. In the chosen region, the corresponding Borel curve to determine the mass of  $K^*\bar{K}^*$  is shown in the left panel of FIG. 2, and we extract the mass value  $2.02 \pm 0.11$  GeV. In the end, we vary quark masses as well as condensates and arrive at  $2.02 \pm 0.11 \pm 0.04$  GeV for  $K^*\bar{K}^*$  (the former error reflects the uncertainty due to the variation of  $s_0$  and  $M^2$ , and the latter error is resulted from the variation of QCD parameters) or  $2.02 \pm 0.15$  GeV in a concise form. For  $K\bar{K}^*$ , we choose the minimum value of  $M^2$  to be  $0.7$  GeV<sup>2</sup> in view of its OPE convergence. Furthermore, the ratio of pole contribution to continuum contribution from sum rule (5) for  $\sqrt{s_0} = 2.2$  GeV is approximate to 52% at  $M^2 = 1.3$  GeV<sup>2</sup>. Thus, the maximum value of  $M^2$  is taken as  $1.3$  GeV<sup>2</sup> for  $\sqrt{s_0} = 2.2$  GeV. With the similar analysis, the maximum  $M^2$  is taken as  $1.4$  GeV<sup>2</sup> for  $\sqrt{s_0} = 2.3$  GeV; for  $\sqrt{s_0} = 2.4$  GeV, the maximum  $M^2$  is taken as  $1.5$  GeV<sup>2</sup>. The dependence on  $M^2$  for the mass of  $K\bar{K}^*$  from sum rule (6) is shown in the right panel of FIG. 2. Finally, we arrive at  $1.85 \pm 0.09 \pm 0.05$  GeV for  $K\bar{K}^*$  (the first error reflects the uncertainty due to the variation of  $s_0$  and  $M^2$ ,

and the second error is resulted from the variation of QCD parameters) or  $1.85 \pm 0.14$  GeV concisely.

In Ref. [1], it has been suggested that the two states  $Z_{s1}^+$  and  $Z_{s2}^+$  in question should appear near their respective two meson thresholds, namely  $K\bar{K}^*$  and  $K^*\bar{K}^*$ . We would make a comparison between the QCD Sum Rules' results here and the known thresholds. For the  $Z_{s1}^+$  state, the result of QCD sum rule calculation here is approximately  $320 \sim 600$  MeV higher than the  $K\bar{K}^*$  threshold. For the  $Z_{s2}^+$  state, our result is roughly  $90 \sim 390$  MeV higher than the  $K^*\bar{K}^*$  threshold.

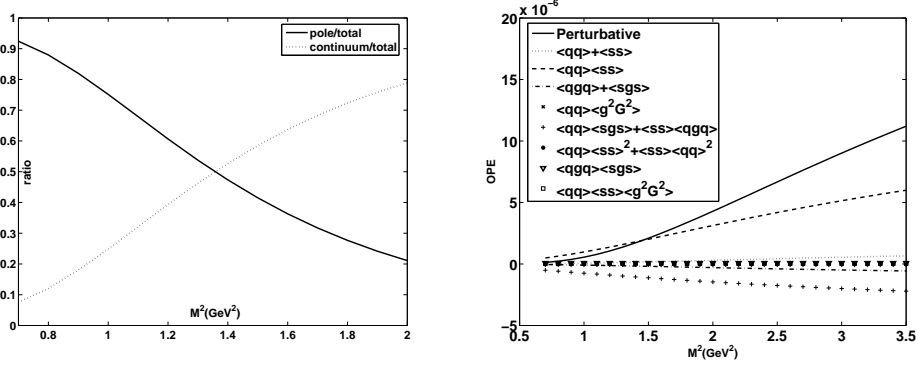


FIG. 1: In the left panel, the solid line shows the relative pole contribution (the pole contribution divided by the total, pole plus continuum contribution) and the dashed line shows the relative continuum contribution from sum rule (10) for  $\sqrt{s_0} = 2.4$  GeV for  $K^*\bar{K}^*$ . The OPE convergence is shown by comparing the perturbative, two-quark condensate, four-quark condensate, mixed condensate, two-quark multiply two-gluon condensate, two-quark multiply mixed condensate, six-quark condensate, mixed multiply mixed condensate, and four-quark multiply two-gluon condensate contributions from sum rule (10) for  $\sqrt{s_0} = 2.4$  GeV for  $K^*\bar{K}^*$  in the right panel.

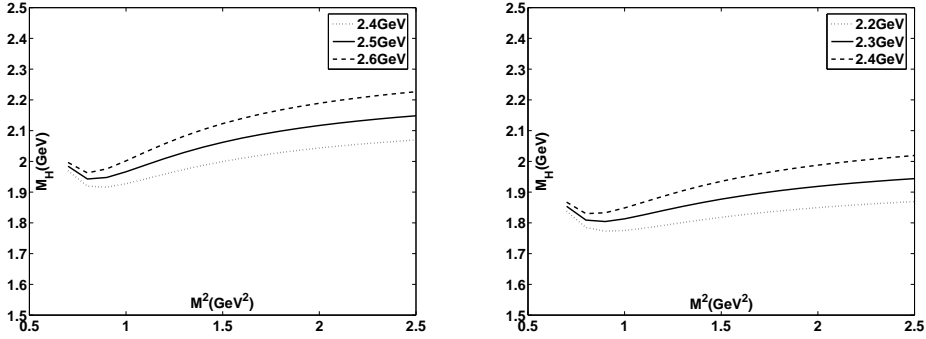


FIG. 2: In the left panel, the dependence on  $M^2$  for the mass of  $K^*\bar{K}^*$  from sum rule (11) is shown. The continuum thresholds are taken as  $\sqrt{s_0} = 2.4 \sim 2.6$  GeV. For  $\sqrt{s_0} = 2.4$  GeV, the range of  $M^2$  is  $0.7 \sim 1.3$   $\text{GeV}^2$ ; for  $\sqrt{s_0} = 2.5$  GeV, the range of  $M^2$  is  $0.7 \sim 1.4$   $\text{GeV}^2$ ; for  $\sqrt{s_0} = 2.6$  GeV, the range of  $M^2$  is  $0.7 \sim 1.5$   $\text{GeV}^2$ . The dependence on  $M^2$  for the mass of  $K\bar{K}^*$  from sum rule (6) is shown in the right panel. The continuum thresholds are taken as  $\sqrt{s_0} = 2.2 \sim 2.5$  GeV. For  $\sqrt{s_0} = 2.2$  GeV, the range of  $M^2$  is  $0.7 \sim 1.3$   $\text{GeV}^2$ ; for  $\sqrt{s_0} = 2.3$  GeV, the range of  $M^2$  is  $0.7 \sim 1.4$   $\text{GeV}^2$ ; for  $\sqrt{s_0} = 2.4$  GeV, the range of  $M^2$  is  $0.7 \sim 1.5$   $\text{GeV}^2$ .

#### IV. SUMMARY AND OUTLOOK

In theory, there could exist two charged strangeonium-like molecular states  $Z_{s1}^+$  and  $Z_{s2}^+$  from an effective Lagrangian study. In this work, we have employed the QCD sum rule method to predict masses of  $Z_{s1}^+$  and

$Z_{s2}^+$ , taking into account contributions of operators up to dimension ten in the OPE. Our final numerical results are  $1.85 \pm 0.14$  GeV for  $Z_{s1}^+$  ( $K\bar{K}^*$ ) and  $2.02 \pm 0.15$  GeV for  $Z_{s2}^+$  ( $K^*\bar{K}^*$ ), which are both above their respective two meson thresholds. One can expect that these results could be helpful for investigating  $Z_{s1}^+$  and  $Z_{s2}^+$  experimentally. We suggest to start the search for these two states in some decay process such as  $Y(2175) \rightarrow \phi(1020)\pi^+\pi^-$  in future experiments, especially Super-B, Belle II and BESIII.

### Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Contract Nos.11105223, 10947016, and 10975184.

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- [1] D. Y. Chen, X. Liu, and T. Matsuki, arXiv:1112.3773 [hep-ph].
  - [2] M. B. Voloshin and L. B. Okun, JETP Lett. **23**, 333 (1976).
  - [3] A. D. Rujula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. **38**, 317 (1977).
  - [4] J. R. Zhang and M. Q. Huang, Commun. Theor. Phys. **54**, 1075 (2010).
  - [5] Y. L. Ma, Phys. Rev. D **82**, 015013 (2010).
  - [6] X. Liu, Z. G. Luo, Y. R. Liu, and S. L. Zhu, Eur. Phys. J. C **61**, 411 (2009).
  - [7] X. Liu and S. L. Zhu, Phys. Rev. D **80**, 017502 (2009).
  - [8] Y. C. Yang and J. L. Ping, Phys. Rev. D **81**, 114025 (2010).
  - [9] N. Mahajan, Phys. Lett. B **679**, 228 (2009); T. Branz, T. Gutsche, and V. E. Lyubovitskij, Phys. Rev. D **80**, 054019 (2009); G. J. Ding, Eur. Phys. J. C **64**, 297 (2009).
  - [10] X. Liu, X. Q. Zeng, and X. Q. Li, Phys. Rev. D **72**, 054023 (2005).
  - [11] C. Z. Yuan, P. Wang, and X. H. Mo, Phys. Lett. B **634**, 399 (2006).
  - [12] X. Liu, Z. G. Luo, and S. L. Zhu, Phys. Lett. B **699**, 341 (2011).
  - [13] C. Meng and K. T. Chao, arXiv:0708.4222; X. Liu, Y. R. Liu, W. Z. Deng, and S. L. Zhu, Phys. Rev. D **77**, 034003 (2008); X. Liu, Y. R. Liu, W. Z. Deng, and S. L. Zhu, Phys. Rev. D **77**, 094015 (2008).
  - [14] M. Nielsen, F. S. Navarra, and S. H. Lee, Phys. Rep. **497**, 41 (2010); N. A. Tornqvist, Phys. Lett. B **590**, 209 (2004); F. E. Close and P. R. Page, Phys. Lett. B **578**, 119 (2004); E. S. Swanson, Phys. Lett. B **588**, 189 (2004).
  - [15] M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys. **B147**, 385 (1979); **B147**, 448 (1979); V. A. Novikov, M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Fortschr. Phys. **32**, 585 (1984).
  - [16] B. L. Ioffe, in The Spin Structure of The Nucleon, edited by B. Frois, V. W. Hughes, and N. de Groot (World Scientific, Singapore, 1997).
  - [17] S. Narison, QCD Spectral Sum Rules (World Scientific, Singapore, 1989).
  - [18] P. Colangelo and A. Khodjamirian, in At the Frontier of Particle Physics: Handbook of QCD, edited by M. Shifman, Boris Ioffe Festschrift Vol. 3 (World Scientific, Singapore, 2001), pp. 1495-1576; A. Khodjamirian, Continuous Advances in QCD 2002/ARKADYFEST.
  - [19] M. Neubert, Phys. Rev. D **45**, 2451 (1992); M. Neubert, Phys. Rep. **245**, 259 (1994).
  - [20] H. X. Chen, X. Liu, A. Hosaka, and S. L. Zhu, Phys. Rev. D **78**, 034012 (2008).
  - [21] H. X. Chen, A. Hosaka, and S. L. Zhu, Phys. Rev. D **76**, 094025 (2007); Phys. Rev. D **78**, 054017 (2008); Phys. Rev. D **78**, 117502 (2008).
  - [22] H. X. Chen, A. Hosaka, H. Toki, and S. L. Zhu, Phys. Rev. D **81**, 114034 (2010).
  - [23] A. L. Zhang, T. Huang, and T. G. Steele, Phys. Rev. D **76**, 036004 (2007).
  - [24] Z. G. Wang and W. M. Yang, Eur. Phys. J. C **42**, 89 (2005); Z. G. Wang, Nucl. Phys. A **791**, 106 (2007).
  - [25] T. V. Brito, F. S. Navarra, M. Nielsen, and M. E. Bracco, Phys. Lett. B **608**, 69 (2005).
  - [26] J. R. Zhang and M. Q. Huang, Phys. Rev. D **80**, 056004 (2009); J. Phys. G: Nucl. Part. Phys. **37**, 025005 (2010); JHEP **1011**, 057 (2010); Phys. Rev. D **83**, 036005 (2011).
  - [27] J. R. Zhang, M. Zhong, and M. Q. Huang, Phys. Lett. B **704**, 312 (2011).
  - [28] K. Nakamura *et al.*, (Particle Data Group), J. Phys. G **37**, 075021 (2010).

- [29] L. J. Reinders, H. R. Rubinstein, and S. Yazaki, Phys. Rep. **127**, 1 (1985).